Asteroid Exploration and Exploitation

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Think Outside the Box…

…if you can!

The NEA Population

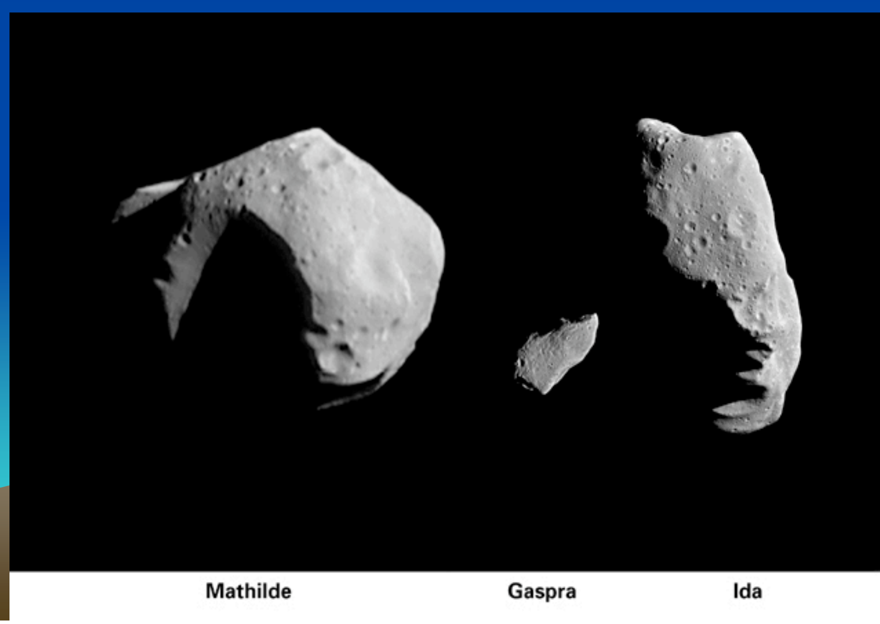
- About 1200 one-kilometer-sized NEAs
- About 400,000 100-m sized NEAs
- Periods generally 0.9 to 7 years
- Orbital inclinations generally 10-20^{o}
- Eccentricities 0 to 0.9; mostly near 0.5
- About 30% will eventually hit Earth
- About 20% are easier to land on than the Moon

Data on NEO Compositions

- Over 10,000 analyzed meteorites, most of which are from NEO parents
  - About 50 different classes from steel to mud
- Remote sensing UV/vis/near IR
  - Many spectral classes; some match meteorites
- Spacecraft *in situ* measurements
- Sample return (*Hayabusa* (?))

Traits of Economically Desirable NEAs

- Easy access from LEO/HEEO
- Easy return to LEO/HEEO
- Abundance of useful materials
- Simple, efficient processing schemes



Easy Access from LEO Means:

- Perihelion (or aphelion) close to 1 AU
- Small eccentricity
- Low inclination

These factors combined allow low outbound ΔVs (from LEO to soft landing)

About 240 km-sized NEAs have $\Delta V_{out} < 6$ km s^{-1} (vs. 6.1 for the Moon)

Easy Return to LEO Means:

- Perihelion (aphelion) close to 1 AU
- Small cross-range distance between orbits
- Favorable orbital phasing
- Use of aerocapture at Earth

These factors allow low inbound ΔVs (from asteroid surface to LEO).

Many NEAs have ΔV_{in} < 500 m s^{-1} (some as low as 60 m s^{-1}, compared to 3000 m s^{-1} for Moon)

Abundance of Useful Materials 1

- What are the most useful materials?
  - Water (ice, -OH silicates, hydrated salts) for
    - Propellants
    - Life support
  - Native ferrous metals (Fe, Ni) for structures
  - Bulk regolith for radiation shielding
  - Platinum-group metals (PGMs) for Earth
  - Semiconductor nonmetals (Si, Ga, Ge, As,…) for Earth or Solar Power Satellites

Abundance of Useful Materials 2

- Comparative abundances
  - Water
    - C, D, P chondrites have 1 to >20% H_2O; extinct NEO comet cores may be 60% water ice
    - Mature regolith SW hydrogen reaches maximum of about 100 ppm in ilmenite-rich mare basins (water equivalent 0.1% assuming perfect recovery)
  - Metals
    - To 99% in M asteroids; 5-30% in chondrites
    - Lunar regolith contains 0.1 to 0.5 % asteroidal metals

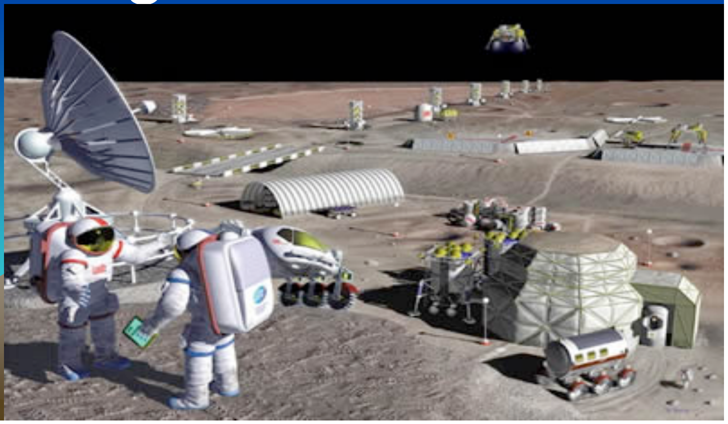
Simple, Efficient Processing Schemes

- "Simple and Efficient"
  - Low energy consumption per kg of product
  - Processes require little or no consumables
  - Few **mechanical** parts
  - Modular design for ease of repair
  - Highly autonomous operation
  - On-board AI/expert systems for process control
  - Self-diagnosis and self-repair capabilities
  - Maximal use of low-grade (solar thermal) energy
  - Regenerative heat capture wherever possible

Examples of Processing Schemes

"Industrial Cosmochemistry"

- Ice extraction by melting and sublimation of native ice using solar or nuclear power
- Water extraction from –OH silicates or hydrated salts by solar or nuclear heating
- Electrolysis of water and liquefaction of H/O
- Ferrous metal volatilization, separation, purification, and deposition by the gaseous Mond process
  - $Fe^{o}(s) + 5CO \leftrightarrow Fe(CO)_5(g)$
  - $Ni^{o}(s) + 4CO \leftrightarrow Ni(CO)_4(g)$



Magnitude of NEA Resources

- Total NEA mass about 4×10^{18} g
- About 1×10^{18} g ferrous metals
- About 1×10^{18} g water
- Earth-surface market value of NEA metals
  - Fe iron \$300/Mg x 10^{12} Mg = \$300 T
  - Ni \$28000/Mg x 7×10^{10} Mg = \$2000 T
  - Co \$33000/Mg x 1.5×10^{10} Mg = \$500 T
  - PGMs \$40/g x 5×10^{7} Mg = \$2000 T

High-value Imports for Earth

- PGM prices (\$US/troy ounce)
  - Pt \$1032
  - Pd 276
  - Os 380
  - Ir 380
  - Rh 4650
  - Ru 165
- Nonmetals for semiconductors
  - In(\$27/toz), Ga (\$16/toz), Ge, As, Sb, Se…

High-Utility Materials for Use in Space

- Structural metals
  - High-purity iron from Mond process
    - 99.9999% Fe: strength and corrosion resistance of stainless steel
  - High-precision chemical vapor deposition (CVD) of Ni in molds
    - Custom CVD of Fe/Ni alloys
- Bulk radiation shielding
  - Regolith, metals, water (best)

One Small Metallic NEA: Amun

- 3554 Amun: smallest known M-type NEA
- Amun is 2000 m in diameter
- Contains about 30x the total amount of metals mined over human history
- Contains 3×10^{16} g of iron
- Contains over 10^{12} g of PGMs with Earth-surface market value of about $40 T

Sites of Demand for NEA Materials

- LEO
  - Propellants for GTO/GEO/HEEO/Moon/Mars
  - Radiation shielding
- GEO
  - Structural metals for Solar Power Satellites
  - Station-keeping propellants
  - Photovoltaics for SPS

Propellants from Water

- Direct use of water as propellant
  - Solar Thermal Propulsion-- STP ("Steam rocket")
  - Nuclear Thermal Propulsion– NTP

- Electrolysis of water to H/O
  - H_2 STP
  - H_2 NTP
  - H_2/O_2 chemical propulsion →

NEAs as Traveling Hotels

- Typical NEAs have perihelia near Earth and aphelia in the heart of the asteroid belt
- NEA regolith provides radiation shielding
- Asteroid materials provide propellants
- Earth-Mars transfer orbits possible
- Traveling hotels/gas stations/factories… colonies?

The Martian Connection

- NEAs as transportation aids
  - Traveling gas stations
  - Traveling hotels
- Manned Mars mission rehearsals
- Phobos and Deimos as former NEAs parked in areocentric orbit

Space Colonization

- Asteroids are primarily mine sites, not resorts or suburbs
- Early exploitation should be simple, energy-efficient, and unmanned
- People will arrive as needed
- This vision dates back to Tsiolkovskii (1903) and Goddard (1908)
- Space colonization is not a goal; if it happens it will be as a response to compelling opportunities

Asteroids Over the Moon?

- Asteroid strong points:
  - Low ΔV_{out}
  - Very low ΔV_{in}
  - Resource richness and diversity
- Lunar strong points:
  - Short trip times
  - Helium-3 recovery?

Rôles of Private Enterprise

- Low-cost *competitive* access to space
- Large-scale *competitive* mineral exploration
- Efficient, *competitive* resource exploitation
- Construction and operation of communication and transportation hubs (LEO, GEO, HEEO, lunar L1, etc.)

We CANNOT AFFORD a centrally-controlled, duplication-free, government-dominated effort

Tsiolkovskii's (1904) 14 Points #1-7

1. Rocket engine tests
2. Single stage rocket flights (1926)
3. Multi-stage rocket flights (1952)
4. Unmanned orbital flight (1957)
5. Manned orbital flight (1961)
6. Prolonged manned orbital flight (1965)
7. Experimental air recycling using plants

Tsiolkovskii's points 8-14

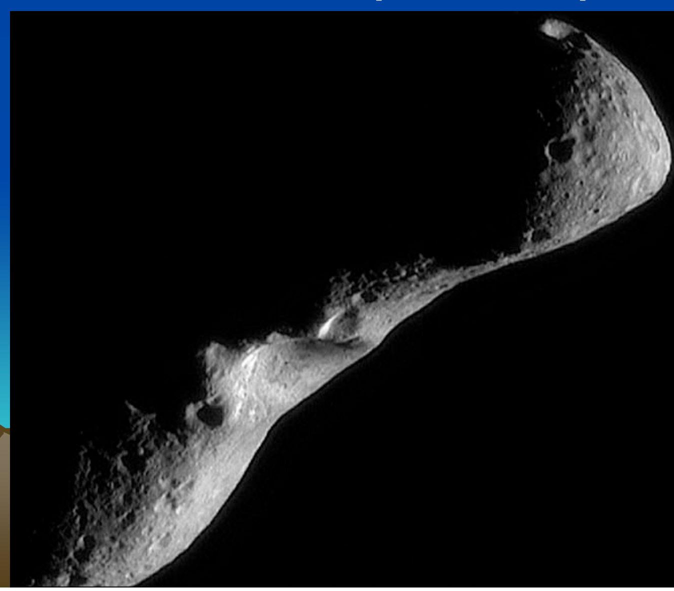
8. Spacesuits for use outside spacecraft (1965)
9. Space agriculture as a source of food
10. Earth-orbiting space colonies
11. Use of solar energy for transportation and power in space
12. Exploitation of asteroid resources
13. Space industrialization
14. Perfection of mankind and society

Suggested Reading

- JS Lewis and RA Lewis, *Space Resources: Breaking the Bonds of Earth, 407 pp.* Columbia Univ. Press, (1987)
- MF McKay, DS McKay and MB Duke, eds., *Space Resources*, 942 pp. NASA SP-509 (1992)
- JS Lewis, MS Matthews and M Guerrieri, eds., *Resources of Near-Earth Space,* Univ. of Arizona Press, Tucson. 977 pp. (1993)
- JS Lewis, *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets,* Addison-Wesley, Reading, MA. 274 pp. (1996)

Legal Regime for Space Resource Utilization

JS Lewis and CF Lewis, A Proposed International Legal Regime for the Era of Private Commercial Utilization of Space. *The George Washington International Law Review* **37**, 745-767 (2005).



A New, Broader Perspective

(Back to the Future of Tsiolkovskii and Goddard)